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Uncertainty Analysis of Squeeze-Type Regulation Method for Equal Expulsion of Parallel Tanks

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Abstract. Focused on the problem of unbalanced propellant consumption in parallel tanks of propulsion system, a squeeze-type regulation method based on the gas law method was discussed in the paper. Taking the tank system as the research object, the thermodynamic models under isothermal, adiabatic and other conditions were given and the factors affecting the uncertainty of the model were analysed. The results show that the measurement uncertainty of the model mainly comes from the pressure measurement accuracy and the volume measurement accuracy. The model was applied to different cases and the influence law of different tank parameters on the model uncertainty was studied. It is found that under the premise of the fixed pressure difference of the parallel tanks, the uncertainty of the regulation model is almost linear with the regulation amount. In addition, the relative uncertainty of the model can be reduced effectively by improving the pressure difference of the parallel tanks. The accuracy of the regulation model can reach to 7.7%, which can meet the requirements for on-orbit use.

1. Introduction

Considering the bearing capacity and configuration, medium and large spacecrafts generally adopt the bipropellant propulsion systems with four-tank design [1~4]. Generally, the tanks are symmetrically arranged in the satellite, and the same kind of propellant is used in parallel to ensure that the center of the propellant is on the central axis of the satellite. When the propellant expulsion difference of the parallel tanks is large, the deviation of the remaining propellant in the tanks is also too large, which causes the satellite centroid to be skewed and the disturbance torque to become larger, which makes the attitude control thrusters work frequently and the propellant utilization efficiency decrease.

The expulsion of the parallel tanks is generally adjusted by the flow resistance matching method [5~6], but the requirements of simulation accuracy and ground test are high. Controlling propellant flow rate of parallel tanks through the switching strategy of the latch valve during the orbit transfer phase can also effectively solve the problem of the unbalanced propellant consumption in parallel tanks, but the implementation is difficult and may affect the performance of the engine. There is another way to squeeze the propellant from the tank with more remaining amount to the tank with less remaining amount by adjusting the pressure of the tanks after the end of the orbit transfer phase. The squeeze-type regulation method is simple and has strong operability.

In this paper, the squeeze-type regulation method for the equal expulsion of parallel tanks is described. The thermodynamic models under isothermal, adiabatic and other conditions were given. The model uncertainty was analyzed from the aspects of environment and measurement parameters.



The influence law of different parameters on the model uncertainty was studied, and the reference to the specific implementation of the regulation method is provided.

2. Description of the model

2.1. Overview of regulation process

The principle of the squeeze-type equal expulsion regulation system is shown in Figure 1. The system consists of the following parts:

Helium tank: High-pressure helium is stored in the helium tank and flows into the propellant tanks through the pressure regulator.

Latch valve: The latch valves are arranged upstream and downstream of the propellant tanks to control the gas inflow and the propellant outflow.

Propellant tank: The propellant tank is used to store propellant, which is filled with helium to squeeze the propellant to the engine or thrusters inlet.

Pressure transducer: The pressure transducer is used to monitor the pressure change of the propellant tank. The accuracy of the pressure transducer directly affects the strategy and final accuracy of the regulation method.

Temperature sensor: The temperature sensor is placed on the wall of the propellant tank to monitor the temperature change.

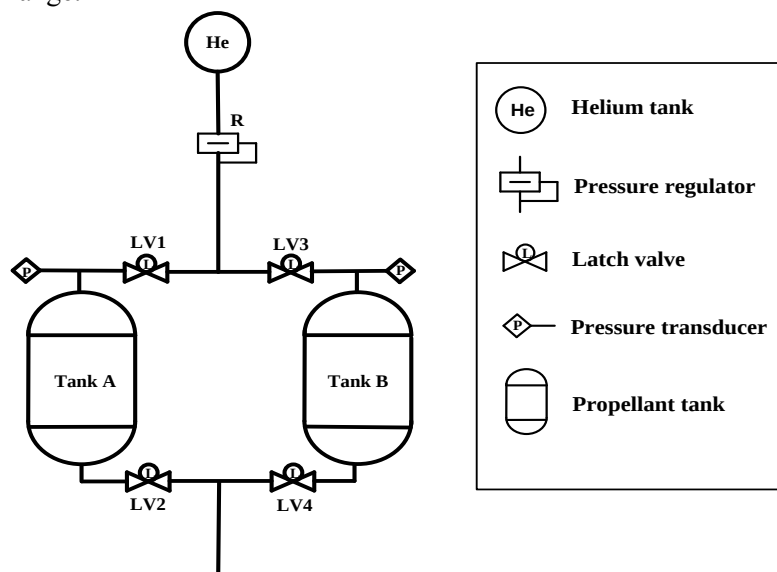


Figure 1. Regulation system schematic.

The steps of regulation method are as follows:

1) At the end of the orbital transfer, close the downstream latch valves LV2 or LV4 to prevent the propellant flow between the two parallel tanks. The pressure and temperature of the tank are recorded, and the volume of the gas in the tank A and tank B can be expressed as

$$V_{gAi} = V_t - \frac{m_{Ai}}{\rho_A}, \quad V_{gBi} = V_t - \frac{m_{Bi}}{\rho_B} \quad (1)$$

Where, V_t is the nominal volume of the propellant tank, m_{Ai} and m_{Bi} are the propellant remaining of tank A and tank B. ρ_A and ρ_B are the density of tank A and tank B.

2) By controlling the latch valve LV1 and LV3, the pressure of the tank A and the tank B is conditioned to a predetermined pressure which is recorded as P_{Ai} and P_{Bi} , the pressure of the helium in the tank A and tank B can be calculated as follows:

$$P_{gAi} = P_{Ai} - P_{vAi}, \quad P_{gBi} = P_{Bi} - P_{vBi} \quad (2)$$

Where, P_{vAi} and P_{vBi} are the saturated vapor pressure in the tank A and tank B.

3) Open the downstream latch valves LV2 and LV4, and pressure difference will repel the propellant from one tank into another tank. While the pressure of parallel tanks reaches equilibrium, the regulation process is completed and the adjusted volume ΔV_l is obtained.

2.2. Calculation model

Assuming that the gas is ideal and the tank system is in thermodynamic equilibrium state before and after the regulation, ignoring the influence of propellant density and expecting that some propellant in tank B will be squeezed into tank A. Various thermodynamic models are discussed and established under different assumptions in the following.

1) Isothermal model

Assuming the regulation amount is small or the heat exchange is timely in the regulation process, the gas temperature in the propellant tank is kept consistent. Ignoring the saturated vapor pressure, the governing equation under the assumption of isothermal is given by

$$P_{Bi} = P_{Ai} \left(1 + \frac{\Delta V_l}{V_{gBi}} \right) \left(1 - \frac{\Delta V_l}{V_{gAi}} \right)^{-1} \quad (3)$$

2) Adiabatic model

Assuming that the entire regulation process takes a short time, the temperature change caused by the volume change of the gas is dominant, and the heat exchange between the gas and objects such as tank wall, propellant and external environment is negligible. The regulation process is adiabatic. Ignoring the saturated vapor pressure, the governing equation is given by

$$P_{Bi} = P_{Ai} \left(1 + \gamma \frac{\Delta V_l}{V_{gBi}} \right) \left(1 - \gamma \frac{\Delta V_l}{V_{gAi}} \right)^{-1} \quad (4)$$

Where, γ is the adiabatic coefficient of helium.

3) non-isothermal and non-adiabatic model

Assuming that the propellant tank pressure change during the regulation process is small and the propellant temperature is almost unchanged, the governing equation is given by

$$\begin{cases} P_{Bi} = \left(P_{Ai} - P_{vAi} \right) \left(1 + \frac{\Delta T_{gA}}{T_{gAi}} \right) \left(1 - \frac{\Delta V_l}{V_{gAi}} \right)^{-1} + P_{vAe} - P_{vBe} \left(1 + \frac{\Delta V_l}{V_{gBi}} \right) \left(1 + \frac{\Delta T_{gB}}{T_{gBi}} \right)^{-1} + P_{vBi} \\ \Delta T_{gA} \approx (\gamma - 1) T_{gAi} \left(\frac{\Delta Q_A}{P_{gAi} V_{gAi}} + \frac{\Delta V_l}{V_{gAi}} \right) \\ \Delta T_{gB} \approx (\gamma - 1) T_{gBi} \left(\frac{\Delta Q_B}{P_{gBi} V_{gBi}} - \frac{\Delta V_l}{V_{gBi}} \right) \\ P_{vAe} \approx P_{vAi}, \quad P_{vBe} \approx P_{vBi} \end{cases} \quad (5)$$

Where, P_{vAe} , P_{vBe} are the saturated vapor pressure after the regulation, T_{gAi} , T_{gBi} are the gas temperature before the regulation. ΔQ_A , ΔQ_B are the gas thermal energy change in tank A and tank B. ΔT_{gA} , ΔT_{gB} are the temperature change of gas in tank A and tank B.

The calculation of the non-isothermal and non-adiabatic model is complicated, it is not only difficult to quantitatively analyze the heat exchange behavior of the tanks, but also unsuitable for the rapid implementation of the active regulation on the orbit. The isothermal model and the adiabatic

model are simple to calculate. Although the assumption of gas state is different from the actual regulation process, the model can be corrected by ground test or previous on-orbit regulation data.

3. Error analysis

The calculation model includes effects of the pressure measurement, volume measurement, temperature measurement and the non-ideal gas effects (compressibility) on the regulation accuracy..

For ideal gas, assuming that the propellant temperature changes are negligible, and introducing the concept of polytropic process, the following form of the governing equation can be obtained:

$$\Delta V_l = (P_{Bi} - P_{Ai}) \left(n_B (P_{Ai} - P_{vAi}) \left(V_t - \frac{m_{Bi}}{\rho_B} \right)^{-1} + n_A (P_{Bi} - P_{vBi}) \left(V_t - \frac{m_{Ai}}{\rho_A} \right)^{-1} \right)^{-1} \quad (6)$$

n_A, n_B are the polytropic exponent of tank A and tank B, respectively.

Using conventional techniques, the uncertainty in ΔV_l can be expressed in terms of the measurement uncertainties of $P_{Ai}, P_{Bi}, P_{vAi}, P_{vBi}, m_{Ai}, m_{Bi}$ and V_t et al.

$$U_{\Delta V_l}^2 = \left(\frac{\partial \Delta V_l}{\partial P_{Bi}} U_P \right)^2 + \left(\frac{\partial \Delta V_l}{\partial P_{Ai}} U_P \right)^2 + \left(\frac{\partial \Delta V_l}{\partial P_{vBi}} U_{P_v} \right)^2 + \left(\frac{\partial \Delta V_l}{\partial P_{vAi}} U_{P_v} \right)^2 + \left(\frac{\partial \Delta V_l}{\partial V_t} U_{V_t} \right)^2 + \left(\frac{\partial \Delta V_l}{\partial m_{Ai}} U_m \right)^2 + \left(\frac{\partial \Delta V_l}{\partial m_{Bi}} U_m \right)^2 \quad (7)$$

Where U is the uncertainty of a measured or computed value.

Obviously, while $n_A = n_B$, the relative uncertainty is independent of the polytropic exponent. Therefore, using Equation(7) for uncertainty analysis is comprehensive and feasible.

The uncertainty analysis can determine the relative importance of each of the sources of uncertainty. This is useful for assessing the feasibility of making improvements to the regulation. The error distribution function UPC is defined as:

$$UPC(x_i) = \left| \frac{U(x_i)}{U_{\Delta V_l}} \right| \times 100 \quad (8)$$

Where, x_i is the source of each uncertainty, $U(x_i)$ is the uncertainty component associated with x_i .

3.1. Measurement values

The sample set of readings used for the uncertainty analysis is given in Table 1. Taking NTO propellant tanks as an example.

Table 1. Sample set of various parameters.

Symbol	Value	Symbol	Value
P_{Bi}	1.65MPa	U_P	$\pm(0.01 \sim 0.1)\%FS$
P_{Ai}	1.60MPa	U_{P_v}	$\pm 0.005MPa$
m_{Bi}	320Kg	U_{V_t}	$\pm 0.05\%$
m_{Ai}	300Kg	U_m	$\pm 0.5\%$

3.2. Results and Discussion

Figure 2 shows the quantitative variation in UPC with the uncertainty in the propellant tank pressure

sensor varies from 0.01% FS to 0.1% FS. It can be noted that the saturated vapor pressure error has little effect on the model accuracy. Correspondingly, the gas volume measurement accuracy and the pressure sensor accuracy have a significant influence on the overall model accuracy. Therefore, the accuracy of the regulation method can be improved effectively by using high-precision pressure sensors and adopting high-precision propellant gauging techniques.

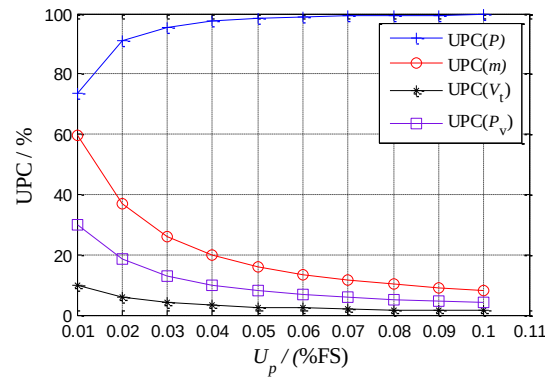


Figure 2. Variation in UPC with uncertainty in tank pressure sensor

4. Effect of tank parameters on model uncertainty

During the ground test, it was found that the actual regulation process was between the isothermal process and adiabatic process. In order to analysis the effect of tank parameters on the relationship between model uncertainty and regulation amount, set $n_A = n_B = 1.35$ and calculate the model uncertainty under different assumptions and tank parameters (tank pressure varies from 1.4MPa to 1.8MPa, propellant remaining varies from 200kg~800kg).

Assuming $\Delta m = m_{Bi} - m_{Ai} = 20\text{kg}$, the relationships between the model uncertainty and the regulation amount with different parallel tanks pressure differences are shown in Figure 3. It can be observed that the difference between the maximum uncertainty and the minimum uncertainty of the model is small with different values of ΔP . The model uncertainty for the same amount of regulation increases as the pressure difference of the parallel tanks decreases. Thus, it can be concluded that relative uncertainty of the regulation model can be reduced by increasing the pressure difference of the parallel tanks during the on-orbit implementation.

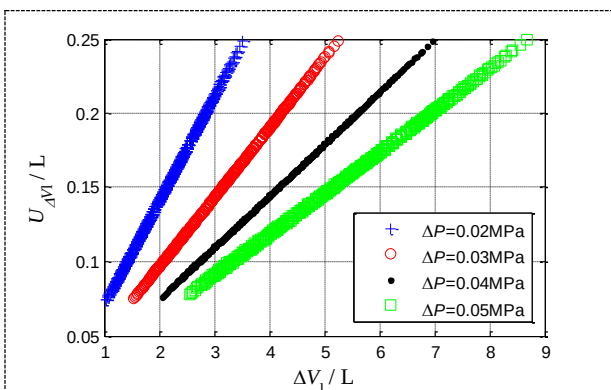


Figure 3. Variation of $U_{\Delta V_i}$ for different tank pressure difference

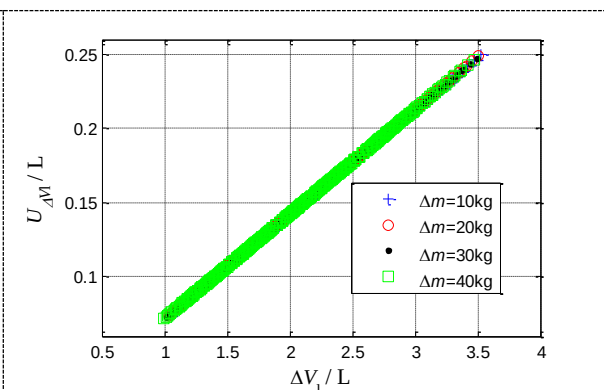


Figure 4. Variation in $U_{\Delta V_i}$ for different propellant remaining difference.

Assuming $\Delta P = P_{Bi} - P_{Ai} = 0.02\text{MPa}$, the relationships between the model uncertainty and the regulation amount under different propellant remaining differences are shown in Figure 4. It can be

observed that several curves are almost completely coincident, thus, the difference in tank propellant remaining has little effect on the relationship between the model uncertainty and the regulation amount.

Through the above analysis, it can be noted that the smaller the pressure difference of the parallel tanks before the regulation, the larger the relative error of the regulation amount. Generally, while the performance of equal expulsion of parallel tanks is less than one percent on-orbit, it can be accepted. Combining with the analysis above, the maximum relative uncertainty of the model can be calculated as shown in Figure 5. While the propellant remaining measurement accuracy is 0.5% and the pressure sensor measurement accuracy is 0.1%, the maximum relative uncertainty of the model is about 7.7%, which can meet the requirements for on-orbit use.

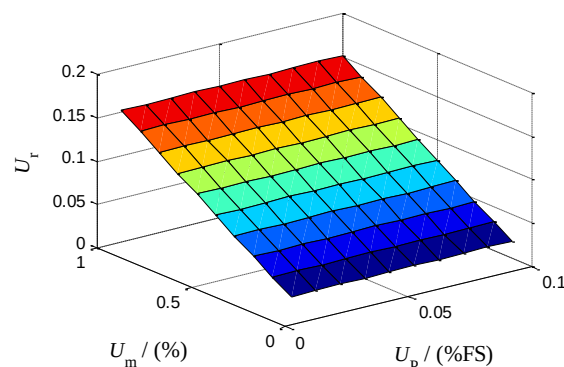


Figure 5. U_r vs U_p and U_m

5. Conclusions

In this paper, the calculation models under various conditions of the squeeze-type regulation method for the equal expulsion of parallel tanks are proposed and the error of the regulation model is analysed. The conclusions are as follows:

- 1) The accuracy of the model mainly depends on the volume measurement accuracy and pressure measurement accuracy of helium in the tanks.
- 2) Under the premise that the pressure differential of the parallel tanks is fixed, the model uncertainty is almost linear with the regulation amount. In addition, increasing the pressure differential of the parallel tanks can effectively reduce the relative error of the regulation model.
- 3) The maximum relative uncertainty of the model is about 7.7% (while $U_m = 0.5\%$, $U_p = 0.1\%$), which can meet the requirements for on-orbit use.

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